

Validating the optimum tilt angle for PV modules in a semi-arid region of South Africa for the winter season

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Abstract—Optimizing the output power of any PV module involves a number of factors, including the setting of the tilt angle. The purpose of this paper is to present empirical evidence validating the optimum tilt angle for PV module installations in semi-arid regions of South Africa for the winter season. The experimental setup includes three identical PV systems where the PV modules were set to different tilt angles as stipulated in the literature. Data was recorded from May to July 2015 using an Arduino board and LabVIEW software. Two power measurements were used to validate the optimum tilt angle as being Latitude plus 10° for the winter season.

Index Terms— Alignment, Azimuth angle, flat surface, incident angle, tilted surface

I. INTRODUCTION

“Despite all the progress climate scientists have made in understanding the risks we run by loading the atmosphere with CO₂, the world is still as addicted to fossil fuels as ever [1].” These words, by Jeff Goodell, highlight the importance of reducing CO₂ emissions and finding solutions to common global problems, like energy shortages. Load shedding has become a common occurrence in South Africa to deal with energy shortages, and is normally the last resort used to prevent a system-wide blackout [2]. It has in many cases a crippling effect on local business[3]. At present, there is no feasible method to store electrical power on a country-wide scale. The installed capacity must therefore be able to deliver peak demand [4]. Predictions are that these energy shortages and load shedding scenarios will increase, thereby necessitating the implementation of alternative energy sources, such as photovoltaic (PV) energy systems.

It must though be stated that PV module efficiencies still remain relatively low, with projections pointing to PV cell efficiency increases from 20% to 25% over the next five years, corresponding to a 25% output power increase [5]. This still, however, indicates that 75% of the absorbed solar energy is actually dumped by the PV module as wasted heat [6]. These low efficiencies necessitate the optimum installation of PV modules according to relevant environmental and site conditions, thereby yielding the optimum amount of output power for a given period.

One of the major factors to consider in PV system installations is the tilt angle of the PV modules. Research by Heywood and Chinnery suggest using tilt angles which are either equal to the Latitude value of the installation site, or then Latitude plus 10° or Latitude minus 10° in the southern hemisphere [7]. The three different tilt angle recommendations are based on seasonal changes, where a lower tilt angle is recommended for summer months while higher tilt angles are recommended for winter months in the southern hemisphere. In the case of fixed mountings, there is the possibility of changing the tilt angle of PV modules for each season. According to Suri et al. a gain of 3% to 4% in energy production can be obtained by having two different seasonal tilts, changing them every 6 months [8].

However many environmental conditions influence the optimal orientation for individual locations, including cloudiness, temperature, shading, dust, rain (which washes away the dust), snow and bird droppings [9]. Research, in a pollution intensive area of South Africa, indicated that, for a stationary PV module, the tilt angle should be at Latitude plus 10° for optimum power yield throughout the year [10]. The research was conducted in an area that was declared an “airshed priority area” due to the concern of elevated pollutant concentrations within the area, being specifically particulates [11]. Would this yearly tilt angle recommendation of Latitude plus 10° hold true for other areas in South Africa, especially for semi-arid regions where excessive dust and heat are experienced?

The purpose of this paper is to present empirical evidence validating the optimum tilt angle for PV modules in a semi-arid region of South Africa during the winter season. Different solar radiation components impacting on the output power of a PV module is firstly presented. Secondly, the context of the research site is established followed by the experimental setup. The research methodology, results and conclusions complete the paper.

II. SOLAR RADIATION COMPONENTS FOR PV MODULES

PV modules receive direct (beam), diffused and reflected radiation during varying atmospheric conditions [12]. Direct radiation is the component where direct line-of-sight exists between the sun and the PV module, with no interruptions such as cloud cover or tree shading. Diffused radiation is the

component scattered by atmospheric constituents such as molecules, aerosols and clouds [13].

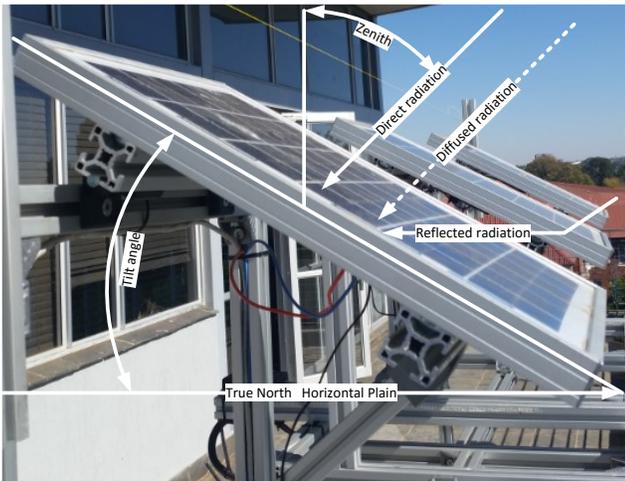


Figure 1. Different radiation beams impacting on a PV module

Reflected radiation occurs when light energy is reflected off trees, buildings or other objects towards the PV module. Fig. 1 illustrates direct, diffused and reflected radiation received by a specific PV module installed at the Central University of Technology (CUT) in Bloemfontein, Free State. On a clear sunny day, the direct radiation component contributes about 90% to the total available solar radiation, with diffused and reflected radiation components supplying the remaining 10% [14]. In the following section the research site will be placed into context.

III. CONTEXT OF THE RESEARCH SITE

South Africa has some of the best solar radiation resources in the world, where the average daily solar radiation varies between 4.5 and 7 kWh / m² [15]. In the heart of South Africa lies the Free State province with Bloemfontein as the provincial capital. The main campus of CUT is located in Bloemfontein where the Faculty of Engineering and Information Technology resides. The co-ordinates of CUT's main campus is 29°07'17.24" S (Latitude) and 26°12'56.51" E (Longitude) [16], and serves as the installation site for this research study. Bloemfontein is a semi-arid region (82% of South Africa is classified as such a region [17] with a daily average global horizontal radiation of 5.15 kWh / m² / day [15].

Annual rainfall in Bloemfontein is around 550 mm [18] with the majority of rains falling in the summer months and water restrictions being imposed during the winter season. Localized dust storms often occur in late winter due to open pan surfaces and large agricultural lands [19]. These conditions are typical of arid and semi-arid regions, which are often characterized by water scarcity, hot dry weather, large areas of poor soils [20] and dust storms [21]. In the following section, the experimental setup that was used for collecting the quantitative data to

determine the optimum tilt angle for winter months at the CUT in Bloemfontein is presented.

IV. EXPERIMENTAL SETUP

The experimental setup consists of three identical PV systems, each comprising a 10W polycrystalline PV module, a 5A solar charger, a 20Ah battery and a 5W LED load (see Fig. 2 for the main block components). All three systems are interfaced with an Arduino board (controlled by LabVIEW software) using a singular data logging interface circuit. This circuit has been reported on by a number of researchers [22-24] and provides power conditioning between the PV system and the data logging system (Arduino and LabVIEW).

The three PV modules were mounted onto an aluminum frame and initially set to the same tilt angle equal to the Latitude of the installation site. The output power of these modules was then recorded and analyzed over a four week period (October 2014), resulting in a coefficient of variation of 1.4%. This coefficient of variation is calculated using the standard deviation and mean of the collected data. This was done to calibrate all three systems to a standard reference, thereby ensuring the validity and reliability of all subsequent measurements. The modules of the identical PV systems were then set to three different tilt angles as listed in Table 1, based on previous research. Reasons for using the LabVIEW software in conjunction with an Arduino board are substantiated in the following sections.

TABLE I. THREE DIFFERENT TILT ANGLES BASED ON RESEARCH DONE BY HEYWOOD [25] AND CHINNERY [26]

Author	Equations of latitude	Tilt angle for Bloemfontein	Time period used
Heywood	$\phi - 10^\circ$	$29^\circ - 10^\circ = 19^\circ$	Summer
Heywood	ϕ	29°	Autumn / Spring
Chinnery	$\phi + 10^\circ$	$29^\circ + 10^\circ = 39^\circ$	Winter

V. LABVIEW

National Instruments LabVIEW is a graphical programming language that has its roots in automation control and data acquisition. It's graphical representation, similar to a process flow diagram, was created to provide an intuitive programming environment for scientists and engineers. The language has matured over the past 20 years to become a general purpose programming environment. LabVIEW has several key features which make it a good choice in an automation environment. These include simple network communication, turnkey implementation of common communication protocols (RS232, GPIB, etc.), powerful toolsets for process control and data fitting, fast and easy user interface construction, and an efficient code execution environment [27].

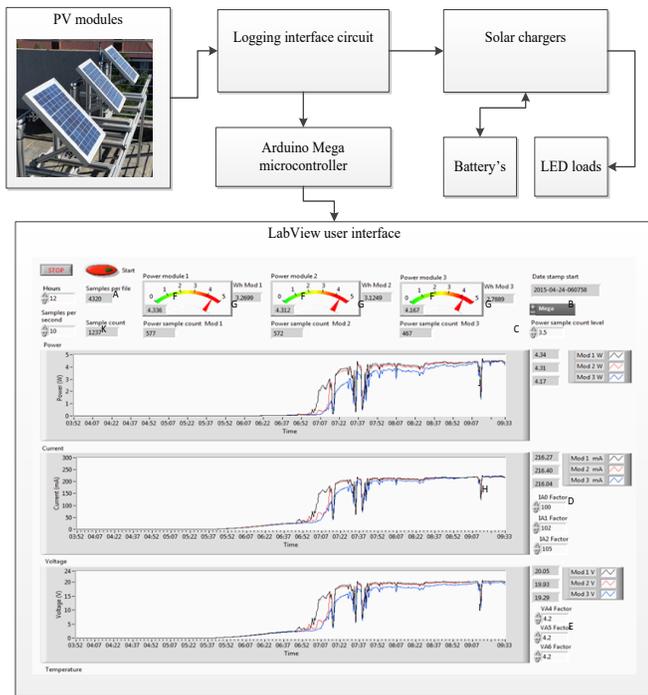


Figure 2. Experimental setup

VI. ARDUINO BORD

The Arduino is an electronic platform designed to simplify the process of studying digital electronics [28] and consists of a microcontroller, a programming language and an Integrated Development Environment (IDE) [29]. Arduino was born to teach Interaction Design, a design discipline that puts prototyping at the centre of its methodology [30]. The designers attempted to design a user-friendly software and hardware interface, making freely available the necessary documentation to support it [31]

VII. MEASUREMENTS

Voltage readings are obtained from the Arduino board by using the analog read function in LabVIEW. The obtained values are then multiplied by a predetermined factor obtained by the calibration process in order to compensate for any interface losses. The immediate value is displayed on the front panel of the LabVIEW software. This value is then filtered by a Butterworth Filter to eliminate high frequency components originating from the Arduino's analog read circuit or from the data logging interface circuit, before being written into a matrix.

Voltage readings from the Arduino board represent PV module output voltages, currents and surface temperatures. Current readings are obtained by measuring the voltage across a low value precision resistor (10Ω 10W 1%). Voltage readings are obtained by using a standard voltage divider circuit (147kΩ resistor in series with a 100kΩ resistor). Temperature readings are obtained by using a thermistor which is connected to the back of the PV module.

One way of comparing the performance of the three PV systems is to record the amount of samples where the output power of each module exceeds a set limit (3.5 W in this research). In order to record the percentage of time that each PV module produces more than 3.5 W of power, a shift register is used in which the value is incremented each time a sample's value is above the set limit. The accumulation of these values is automatically written into a singular file at the end of each day.

A second way of evaluating the performance of each of the three PV systems is to record the Watt hours (Wh) generated by each module for each specific day. This is done by calculating the mean power for a specific number of samples and then multiplying that mean power with the time in hours represented by those samples. This results in an instantaneous Wh value for a specific number of samples taken within a 24 hour period. The LabVIEW user interface is shown in the experimental setup in Fig. 2,

Figure 2 where the following is discernible [28]:

- the total amount of samples that are to be recorded and written to a single file (see A);
- the Arduino board that is used for the sampling (see B);
- the set limit for the power sample count (see C);
- the calibration factor for the current (see D) and voltage of each module (see E);
- the instantaneous power for each module (see F);
- the accumulated Wh for each module (see G),
- a limited logged history as well as the instantaneous values of the current (see H), voltage (see I) and power (see J); and

the total sample count which has been completed (see K)

VIII. RESEARCH METHODOLOGY

The purpose of this research is to present empirical evidence validating the optimum tilt angle for PV modules in a semi-arid region of South Africa during the winter season. An experimental research design is used where all three PV modules were initially set to the same tilt angle of 29° (Latitude value of the installation site). Four weeks of data (October 2014) was recorded to observe any significant differences between the three systems, thereby enabling calibration to a standard reference. A coefficient of variation of 1.4% was calculated indicating that all three systems were performing equally well.

The PV modules were then set to three different tilt angles, resulting in only one different variable (See Figure 3). All three PV systems were equally exposed to all other relevant variables (environmental conditions, orientation angles, charge controllers, battery's etc). Data was recorded from May to July of 2015 which corresponds to the winter season for the installation site. Power sample counts above 3.5 W and Wh results were used to determine which tilt angles yielded the highest output power for this period. PV surface temperatures

were also recorded with the data depicted in figures and tables in the next section.

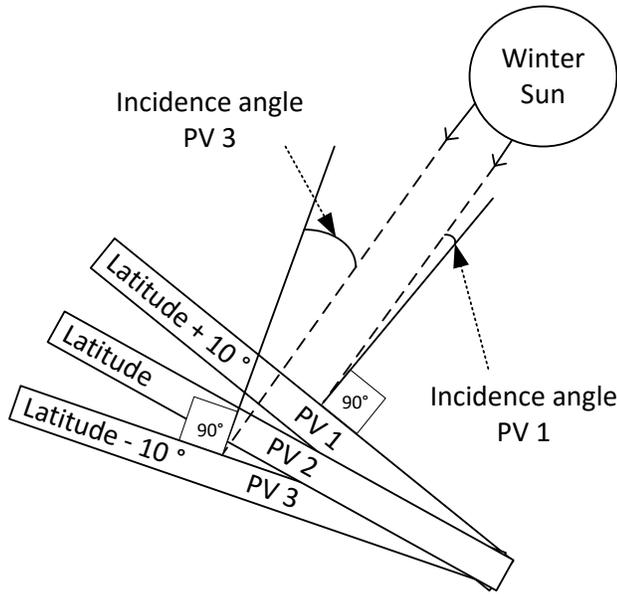


Figure 3. PV module setup for May to July 2015 with incidence angle for PV 1 and PV 3 indicated

IX. RESULTS AND DISCUSSION

Two measurements, namely the amount of power samples above 3.5 W and Wh per day were used to validate the optimum tilt angle of the PV modules. Fig. 4 depicts the number of power samples above 3.5 W for July 2015. It is evident that the sample count for PV 1 (tilt angle of Latitude plus 10°) is generally higher than that for PV 2 (tilt angle of Latitude) and PV 3 (tilt angle of Latitude minus 10°). All three PV modules follow the same trend, showing the influence of the other variables (including the environmental and climate conditions) on their output power. A graph was obtained for each of the three months after which the average monthly values were calculated and used to produce Fig. 5.

Fig. 5 validates the Latitude plus 10° tilt angle (PV 1) as yielding the highest amount of output power with regard to the sample count above 3.5 W. Its average value count of 1976 is more than 200 counts higher than the Latitude minus 10° count (1745). Noteworthy is that all three counts were very similar during May 2015, thereby indicating that the sun's direct radiation component influenced all three systems to roughly the same degree. These results are further verified by the Wh measurements displayed in Figure 6 where PV 1 produced 70Wh on the 18 of July 2015, as compared to the 59Wh produced by PV 3. This can be attributed to the small incident angle of the winter sun on PV1, as compared to PV 3 (see Figure 3 in the previous section).

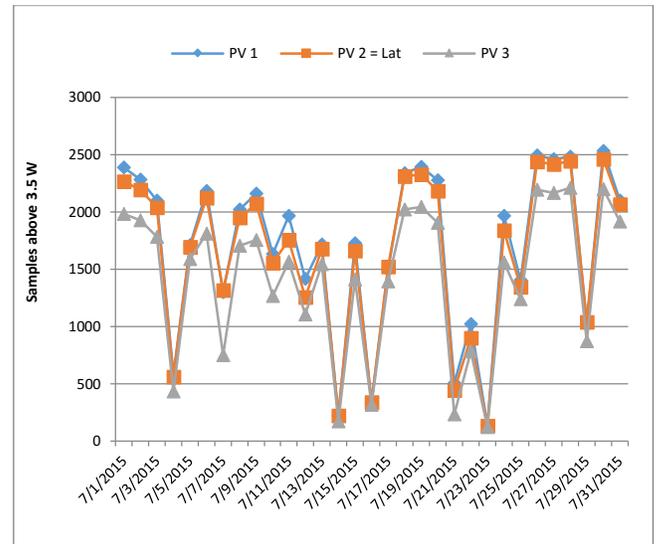


Figure 4. Power samples above 3.5 W for July 2015

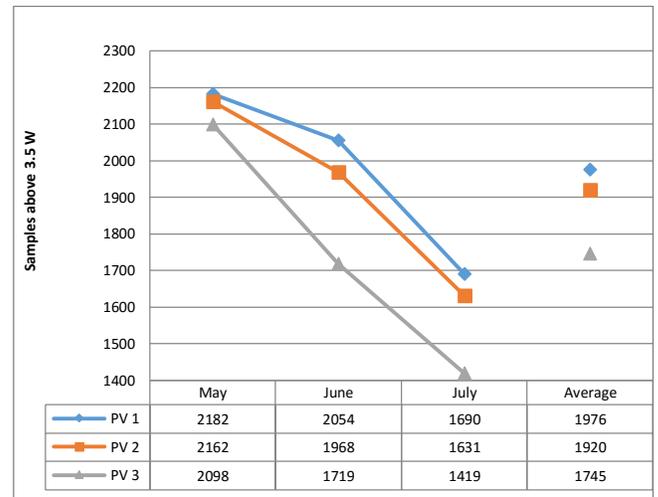


Figure 5. Average power samples above 3.5 W for the three PV modules

The daily values for the Wh measurements in July are shown in Figure 6 the monthly averages in Figure 7 which again validates the Latitude plus 10° tilt angle as yielding the highest output power for this period. PV 1's average output power (63Wh) is more than 6Wh higher than PV 3 (56Wh), set to the Latitude minus 10° tilt angle. The correlation between the samples above 3.5W and the Wh for July 2015 was done with the use of the Pearson Correlation equation. As can be seen in Table 2, there is a strong correlation of 0.88 for all three modules for the July period. Therefore, it can be concluded that the simplified method of counting the number of samples above a specific Wh is valid for determining the maximum output power for a given PV module.

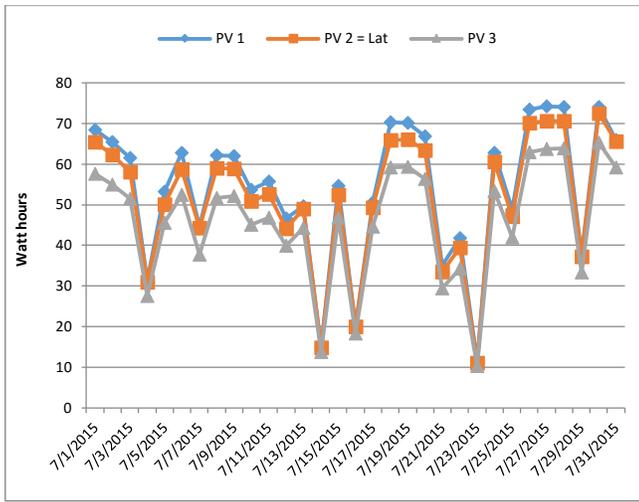


Figure 6. Wh measurements for July 2015

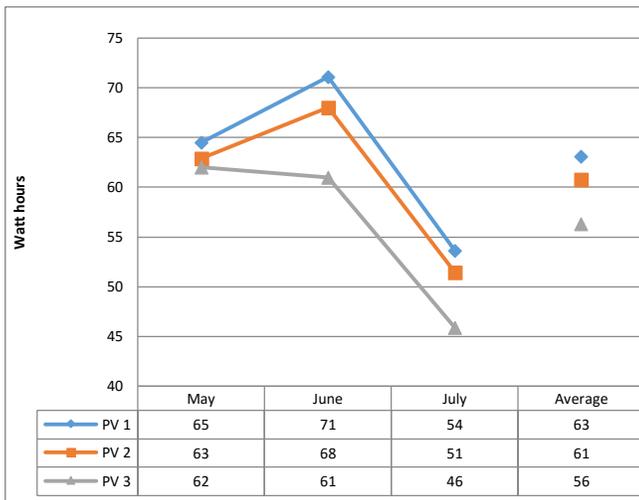


Figure 7. Average Wh measurements for the three PV modules

TABLE II. CORRELATION BETWEEN THE VALUES OF SAMPLES ABOVE 3.5W AND WH FOR JULY 2015

PV module and tilt angle	Correlation of samples above 3.5W and Wh
PV1 tilt angle of latitude plus 10°	0.92
PV 2 tilt angle of latitude	0.86
PV 3 tilt angle of latitude minus 10°	0.86
Average of all 3 modules	0.88

The path of the sun from east to west is shorter during the winter season in the southern hemisphere, with a corresponding lower elevation angle. This implies that a PV module with a higher tilt angle will receive more direct radiation, subsequently generating more heat that needs to be dissipated to the environment. Fig. 8 validate this implication in terms of the PV module's surface temperature for July 2015. PV 1 (tilt angle

equal to Latitude plus 10°) had the highest recorded value of 46°C on the 6 July 2015.

The maximum surface temperature for PV 1 was higher than that for PV 3 during May, June and July (see Fig. 9). These temperature results confirm earlier work done on controlling the surface temperature of PV modules to ensure higher output powers [32].

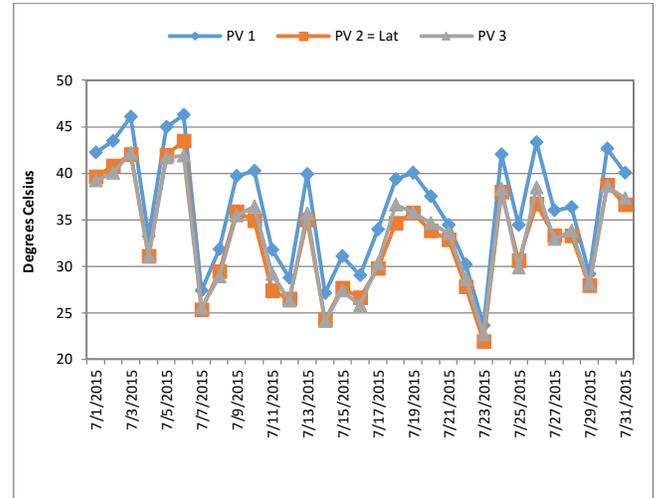


Figure 8. Surface temperatures for the three PV modules in July 2015

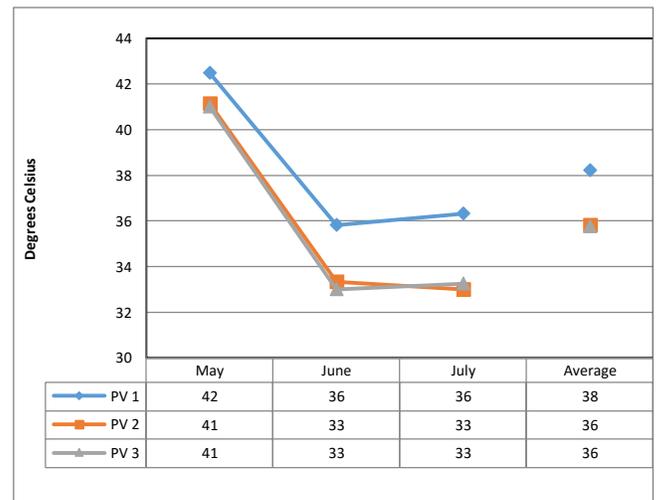


Figure 9. Average surface temperatures for the three PV modules

X. CONCLUSIONS

The purpose of this paper was to present empirical evidence validating the optimum tilt angle for PV modules in a semi-arid region of South Africa during the winter season. Three identical PV systems were installed at CUT in Bloemfontein were specific data was collected over a three month period. Electronic measurement reliability and validity was firstly established by having all three systems set to the same tilt angle, thereby providing a standard of reference for calibration. A coefficient

of variation of 1.4% was established indicating a high level of similarity between the three systems. Three different tilt angles were then used, with PV 1 being set to Latitude plus 10°, PV 2 to Latitude and PV 3 to Latitude minus 10°. Results from the power sample count above 3.5 W and from the Wh calculations indicate that PV 1 produced the highest output power for the months of May 2015 through July 2015.

Based on these results, it is recommended that PV modules be placed at a tilt angle of Latitude plus 10° for semi-arid regions in South Africa during the winter season. This is in contrast to PV module installations for pollution intensive areas [10]. A possible limitation of this study includes the fact that only one research installation site was used over a 3 month period. Making use of a time-lag study and obtaining another set of electronic measurements will serve to validate these results. Moreover, it will further help to establish what the overall yearly optimum tilt angle should be for semi-arid regions in South Africa.

REFERENCES

- [1] Brainy-Quote. (2015, 26 May 2015). *Brainy Quote*. Available: http://www.brainyquote.com/search_results.html?q=Jobs
- [2] D. Chikobvu, C. Sigauke, and A. Verster, "Winter peak electricity load forecasting in South Africa using extreme value theory," *South African Statistical Journal*, vol. 46, pp. 377-394, 2012.
- [3] J. Dekker, M. Nthontho, S. Chowdhury, and S. Chowdhury, "Economic analysis of PV/diesel hybrid power systems in different climatic zones of South Africa," *International Journal of Electrical Power & Energy Systems*, vol. 40, pp. 104-112, 2012.
- [4] M. Kohler, "Differential electricity pricing and energy efficiency in South Africa," *Energy*, vol. 64, pp. 524-532, 2014.
- [5] J. Gomes, J. Junge, and B. Karlsson, "Defining an annual energy output ratio between PV and solar thermal," in *Eurosun 2014, 16-19 September 2014, Aix-les-Bains, France*, 2014.
- [6] H. Chen, S. B. Riffat, and Y. Fu, "Experimental study on a hybrid photovoltaic/heat pump system," *Applied Thermal Engineering*, vol. 31, pp. 4132-4138, 2011.
- [7] S. Armstrong and W. G. Hurley, "A new methodology to optimise solar energy extraction under cloudy conditions," *Renewable Energy*, vol. 35, pp. 780-787, 2009.
- [8] M. Suri, T. Cebecauer, A. Skoczek, and J. Betak, "Solar electricity production from fixed-inclined and sun-tracking C-Si photovoltaic modules in South Africa," 2012.
- [9] J. E. Haysom, K. Hinzer, and D. Wright, "Impact of electricity tariffs on optimal orientation of photovoltaic modules," *Progress in Photovoltaics: Research and Applications*, 2015.
- [10] O. Asowata, A. J. Swart, H. C. Pienaar, and R. M. Schoeman, "Optimizing the output power of a stationary PV panel," presented at the SATNAC 2013, Stellenbosch, South Africa, 2013.
- [11] Government Gazette, "Executive summary of the Vaal Triangle airshed priority area - Air quality management plan," D. o. E. A. a. Tourism, Ed., ed. Pretoria: Government Printer, 2008.
- [12] A. A. El-Sebaei, F. S. Al-Hazmi, A. A. Al-Ghamdi, and S. J. Yaghmour, "Global, direct and diffuse solar radiation on horizontal and tilted surfaces in Jeddah, Saudi Arabia," *Applied Energy*, vol. 87, pp. 568-576, 2010.
- [13] T. V. Ramachandra and B. V. Shruthi, "Spatial mapping of renewable energy potential," *Renewable and Sustainable Energy Reviews*, vol. 11, pp. 1460-1480, 2007.
- [14] S. J. Oh, M. Burhan, K. C. Ng, Y. Kim, and W. Chun, "Development and performance analysis of a two-axis solar tracker for concentrated photovoltaics," *International Journal of Energy Research*, vol. 39, pp. 965-976, 2015.
- [15] S. K. Mulaudzi, M. Muchie, and R. Makhado, "Investigation of the solar energy production and contribution in South Africa: research note," *African Journal of Science, Technology, Innovation and Development: Building technological capabilities in solar energy in Africa*, vol. 4, pp. 233-254, 2012.
- [16] Central University of Technology. (2014, 19 May). *Homepage*. Available: <http://www.cut.ac.za/>
- [17] J. G. Annandale, R. J. Stirzaker, A. Singels, M. Van der Laan, and M. C. Laker, "Irrigation scheduling research: South African experiences and future prospects," *Water SA*, vol. 37, pp. 751-763, 2011.
- [18] M. N. Dinga and P. J. Du Preez, "Grassland communities of urban open spaces in Bloemfontein, Free State, South Africa," *koedoe*, vol. 55, pp. 01-08, 2013.
- [19] G. Wiggs and P. Holmes, "Dynamic controls on wind erosion and dust generation on west-central Free State agricultural land, South Africa," *Earth Surface Processes and Landforms*, vol. 36, pp. 827-838, 2011.
- [20] M. Ramroudi and S. Sharafi, "Roll of cover crops in enhance ecological services," *International Journal of Farming and Allied Sciences*, vol. 2, pp. 1076-1082, 2013.
- [21] D. Doronzo, E. Khalaf, P. Dellino, M. de Tullio, F. Dioguardi, L. Gurioli, et al., "Local impact of dust storms around a suburban building in arid and semi-arid regions: numerical simulation examples from Dubai and Riyadh, Arabian Peninsula," *Arabian Journal of Geosciences*, pp. 1-11, 2014.
- [22] A. Ozemoya, J. Swart, and H. C. Pienaar, "Experimental Assessment of PV Module Cooling Strategies," presented at the SATNAC 2014, Boardwalk Conference Centre, Nelson Mandela Bay, Eastern Cape, South Africa, 2014.
- [23] R. M. Schoeman, A. J. Swart, and H. C. Pienaar, "Negating temperature on photovoltaic panels," presented at the AFRICON 2013, Mauritius, 2013.
- [24] A. J. Swart, H. C. Pienaar, and R. M. Schoeman, "Cost-effective energy monitoring of domestic off-grid PV systems," *JEPE, Journal of Energy and Power Engineering*, vol. 5, pp. 182-188, 2013.
- [25] H. Heywood, "Operating experiences with solar water heating," *Journal of Installation Heat Venting Energy*, vol. 39, pp. 63-69, 1971.
- [26] D. N. W. Chinnery, "Solar heating in South Africa," Pretoria CSIR-Research Report 248, 1981.
- [27] C. Elliott, V. Vijayakumar, W. Zink, and R. Hansen, "National instruments LabVIEW: a programming environment for laboratory automation and measurement," *Journal of the Association for Laboratory Automation*, vol. 12, pp. 17-24, 2007.
- [28] P. Hertzog and A. Swart, "A customizable energy monitoring system for renewable energy systems," presented at the SAUPEC 2015, Resolution Circle Towers in Napier Road in Milpark – Johannesburg, 2015.
- [29] A. Martins, J. Lourenço, T. Patrício, and A. de Alexandria, "Sensor Kinect in a telepresence application," *Computational Vision and Medical Image Processing IV: VIPIMAGE 2013*, p. 151, 2013.
- [30] M. Banzi, *Getting Started with arduino*: "O'Reilly Media, Inc.", 2009.
- [31] L. Buechley and M. Eisenberg, "The LilyPad Arduino: Toward wearable engineering for everyone," *Pervasive Computing, IEEE*, vol. 7, pp. 12-15, 2008.
- [32] A. Ozemoya, J. Swart, H. C. Pienaar, and R. M. Schoeman, "Factors impacting on the surface temperature of a PV panel," presented at the SATNAC 2013, Stellenbosch, South Africa, 2013.